A Status Report on the PBFA II Construction Project*

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Summary

The Particle Beam Fusion Accelerator II (PBFA II) is under construction at Sandia National Laboratories (SNL). PBFA II contains 36 individual power modules configured in a stacked radial geometry and synchronized to provide greater than 3.5 MJ of energy into the vacuum section in a single 55-ns-wide 90-TW peak power pulse. This R&D construction project is being implemented in a fast track schedule mode in which final design of the accelerator components occurs in parallel with the construction of the laboratory building and the accelerator tank. PBFA II is scheduled to become operational in January 1986 with its first multi-module shot into an applied-B ion diode that will generate and transport a beam of lithium ions. Plans are now being made for experimental work on PBFA II beyond the construction phase.

Introduction

The Department of Energy/Office of Inertial Fusion (DOE/OIF) has sponsored research since the early 1970s to investigate the feasibility of producing a controlled thermonuclear reaction in the laboratory using the principles of inertial confinement. The successful demonstration of inertial confinement fusion (ICF) will provide a laboratory capability to investigate nuclear weapon physics and eventually to generate electrical power for commercial use. To provide the capability of investigating ICF ignition and breakeven, DOE/OIF has funded the construction of unique experimental facilities at the three nuclear weapons laboratories. The facilities are

- Neodymium glass lasers, SHIVA, NOVETTE, and NOVA, at Lawrence Livermore National Laboratory
- CO_2 gas lasers, HELIOS and ANTARES, at Los Alamos National Laboratory
- Particle beam accelerators, PBFA I and PBFA II, at Sandia National Laboratory (SNL).

The goal of PBFA II, established in 1980, is to ignite a fusion target with light ions or to determine the level below which ignition is not possible. To accomplish this end, the SNL program for PBFA II has been subdivided into four distinct but overlapping phases:

I. PBFA-II Construction Project (1/80-->1/86)
II. PBFA-II Characterization/Optimization (1/85-->1/87)
III. Source Development (6/86-->9/87)
IV. Target Campaign (9/87 and later)

The objective of Phase I, the PBFA-II construction project, is to design, construct, and test an experimental facility theoretically capable of providing the necessary conditions to demonstrate ICF. The evolution of the PBFA-II concept over several years is described in the next section.

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Project Implementation

Evolution of Conceptual Design

As originally planned in 1978, PBFA II would have been an upgrade of the Electron Beam Fusion Accelerator (EBFA, now PBFA I), to be constructed by adding 36 more modules to the existing machine. However, theoretical analysis by members of the ICF community had indicated by 1979 that breakeven would require more energy and power than this configuration was designed to produce. The conceptual design developed as a result was for an accelerator tailored for light ions: 100 TW, 4 MV, 40 ns FWHM pulse, and 3.5 MJ of energy into the target chamber. This project was authorized by Congress as an FY81 Construction Line Item with construction to begin in February 1981.

In June 1981, Sandia presented DOE/OIF with a request to build a new light-ion PBFA II in the high-bay laboratory building then being constructed for repetitive pulsed power technology. Since ICF reactor technology was being deemphasized in favor of ICF demonstration, DOE/OIF approved this change in scope of the PBFA-II project in June 1981. Given the ICF break-even predictions of 1979 and the constraint of an existing building, engineers of the Sandia Particle Beam Fusion Program began to design the largest, most powerful accelerator that would fit within the shell of an existing high bay laboratory building. The present configuration of PBFA II is shown in Figure 1.

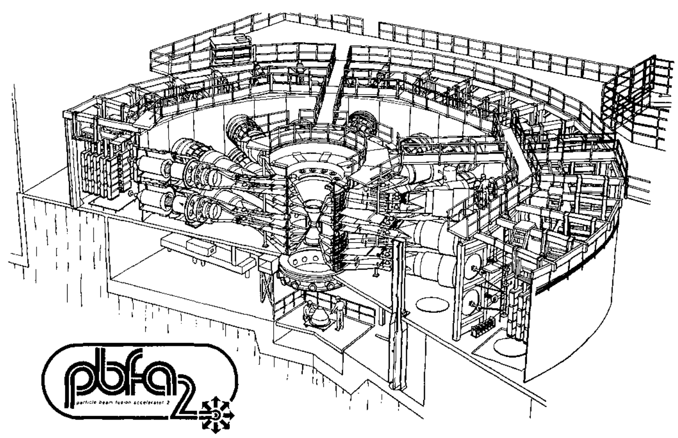

Figure 1. PBFA II.

Organization

The Albuquerque Operations Office (AL) of the Department of Energy (DOE) is responsible for the management of the PBFA-II project implementation. DOE/AL has assigned SNL the responsibility for special construction--the accelerator and specialized support systems--but retains responsibility for standard construction. DOE/AL contracted directly for the design and construction of buildings associated with the project.

A project office was established within SNL during October 1980 to manage the implementation of the Sandia portion of the project. A distributed project team encompassing all the required disciplines or functions was assembled using the matrix mode of management. The project team initially determined what work needed to be

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accomplished, and the project office organized it into a Work Breakdown Structure. The team then distributed accountability for each portion of the work to the appropriate functional representative, developed the project schedule, and defined the overall resources needed to meet the schedule. Work has been accomplished by negotiating work packages between the project office and the accountable functional representative. All work packages are accomplished within the normal functional mode, using staff on an as-needed basis.

Design and Construction Status

Facilities: The main laboratory building was completed in November 1983. Sandia has been constructing the accelerator and installing specialized utilities since taking beneficial occupancy in July 1983. Designed in mid 1980 to be identical to the PBFA-I high-bay laboratory, the building configuration was changed when theoretical analysis showed that breakeven would require a larger accelerator than originally planned. Deleting the floor system and dropping the footings allowed award of a contract in March 1981 for site development, extension of standard utilities, and construction of a generic laboratory building. As the design of PBFA II developed, the interior configuration of the high bay took shape. Experience with the PBFA-I facility also influenced the evolving PBFA-II facility design.

Since completion of the building shell, Sandia has designed and awarded contracts for special-purpose additions and for specialized utilities to support accelerator operation. This work will continue until late 1985. Of the two major building additions, one contains an area, now complete, to house mechanical equipment. This addition also includes another area that will be used first to assemble modules of the vacuum insulator stack and later for general accelerator maintenance. The other building addition is complete and has begun to be used for its major purpose, housing equipment for the insulating gas system. Other work in facilities has included occupancy of the high bay; construction of an electromagnetic-pulse-shielded room where a laser will be located for triggering high-voltage switches; installation of transfer systems for transformer oil and deionized water; and installation of a vacuum system. Radiation shielding to protect the laser will soon be constructed.

Accelerator Support Systems: The major support systems for PBFA II are the transformer oil system, the technical water system, the insulating gas system, the vacuum system, and the pneumatic system. All of these except the insulating gas system are now operational and are capable of supporting accelerator tests, although some connections with the control/monitor system remain to be made.

The oil system was first used to pump transformer oil into the accelerator tank in October 1984. This system has been tested, meets design specifications, and is now supporting tests of the energy storage system. Approximately 530,000 gallons of oil provide electrical insulation in the outer (energy storage) section of PBFA II. The system can filter oil between storage tanks and the accelerator at rates ranging from 500 to 4000 gal/min and can bypass the processing subsystem to pump from storage to the accelerator at up to 8000 gal/min.

The technical water system, which includes storage, transfer, and processing, was procured as a turnkey system and is now operational. This system provides the approximately 550,000 gallons of deionized, bacteria-controlled, deaerated, oil-controlled water used as an electrical insulator and energy storage medium in the pulse-forming section of PBFA II. The processing subsystem supplies water to either the accelerator or bulk storage at rates between 500 and 2000 gal/min. Bypassing the processing subsystem, the transfer subsystem can pump water directly between the accelerator and bulk storage at up to 8000 gal/min. The system meets performance specifications and formal acceptance is imminent.

The insulating gas system has been designed and when constructed will supply high-purity SF_6 gas at a high flow rate. Several components of PBFA II require SF_6, creating a high use rate for each shot. These components include laser-triggered switches in the pulse-forming section, spark gap switches in the Marx generators, the laser trigger assembly, Marx trigger units, and laser standpipes. The project team decided to include a system to recycle SF_6 because of the high cost of the gas—$12,500 per shot if used once and vented to the atmosphere--and the requirement of multiple shots per day. The reprocessing plant for PBFA II will be the largest noncommercial plant in the U.S. The estimated payback on investment will be less than one year.

Full operation of the SF_6 reprocessing plant is not required for the first accelerator shot. Although the plant is scheduled to be complete just before the accelerator begins operation, a temporary reprocessing system with less capability is being implemented in parallel to support initial subsystem testing. In case the main plant is not operational before the first accelerator shot, the first shot will be taken with gas supplied by the temporary reprocessing system. This temporary system will not be able to maintain the processing rates necessary for full accelerator operation. For the main reprocessing plant, piping is in place in the accelerator area, and the major parts of the system--compressors, pumps, tanks, etc.--are on hand. Remaining to be constructed are piping to interconnect these components, distribution of electrical power to operate the plant, and an electrical network for controls.

Vacuum and pneumatic systems are complete and operational. Pumps, piping, and valves of the vacuum system have been successfully tested to the extent possible without the main vacuum chamber. This system was designed to evacuate the target chamber to the vacuum pressure of 5×10^{-5} Torr needed for diode operation. The pneumatic system that drives output transfer switches in the energy storage section has been installed and is functioning. This system also supplies shop air for tools and for air-actuated controls. A separate system, which provides air to divers working in the water-filled pulse forming section, is operational and has met safety and hygiene standards.

Control/Monitor System: The control/monitor (C/M) system is a distributed-intelligence, hierarchical network. In this network, several control/monitor units are connected in a star configuration to a host computer. Besides providing highly automated control of accelerator shots, the C/M system allows remote manual and remote semiautomatic control of most accelerator subsystems and support systems. Each control/monitor unit controls one or more subsystems or support systems. Software development for the C/M system has been going on since April 1984. Extensive wiring has been in progress since early 1985 to provide C/M communication with the accelerator, with facility access and interlocks, and with support systems. In recent months, an effort has been accelerating to develop all the interface information needed to support remote operation of subsystems. The C/M system has been used in tests of the energy storage system since April 1985.

Data Acquisition System: During the time window of an accelerator shot, the data acquisition system (DAS) will record transient waveforms of signals ranging in duration from nanoseconds to tens of microseconds. This data will then be available for analysis. The DAS will include a historical data base of experiments and of accelerator performance. Software has been implemented for a Data General 8000-III computer to control an array of Tektronix 7912AD transient digitizers and LeCroy 6880 multichannel digitizers. It has recently been determined that a second, backup computer is needed, because missing a single accelerator shot due to computer failure would cost more than buying the backup. The backup will also support software development. The Tektronix 7912AD waveform recorders have been installed and are supporting tests of the energy storage system. The LeCroy units, which were specially developed, are not yet ready, but the manufacturer has supplied slower substitutes that can support testing. Implementing the DAS requires extensive software development--five to six man-years. Software for both the DAS and the C/M system must operate reliably; the software quality assurance system was commended in a mid-1984 audit by DOE.

Accelerator Structure: Erection of the basic structure of PBFA II--the accelerator tank and its substructural floor--began in July 1983 and was completed in December 1983. Figure 2 shows the tank at a near-empty stage. Since completion of the tank, work platforms and catwalks have been added over the water section, as shown by Figure 3. Three jib cranes have also been installed at equidistant locations around the oil-water wall; two of these are visible in Figure 3. The mast of each jib crane also supports a stairway from the top of the tank to the floor of the water section. Installation of all accelerator components, now going on, occurs within this structure.

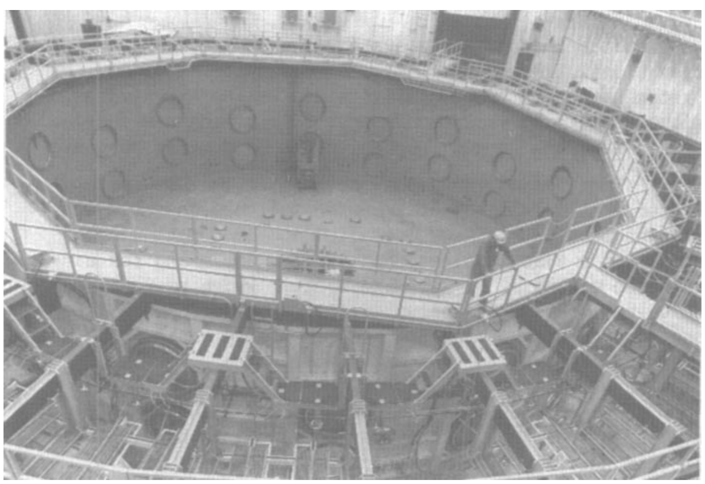

Figure 2. Accelerator tank.

Energy Storage System: The energy storage system has been completely assembled and installed. This system includes 36 Marx generators, a charging subsystem, a firing subsystem, and a system of output-transfer switches; more detail on the system is available elsewhere [2]. The Marx generators were assembled during the second half of 1984, after extensive staging and preassembly [3], a very efficient method that led to completion within budget and schedule. Figure 4 shows a Marx generator being assembled, and Figure 5 shows one being installed in the accelerator tank. The assembled Marx generators were checked out in a testbed consisting of a tank, a control console, and support systems. This testbed, which began operation on schedule in August 1984, will be used to support maintenance of Marx generators throughout the lifetime of PBFA II.

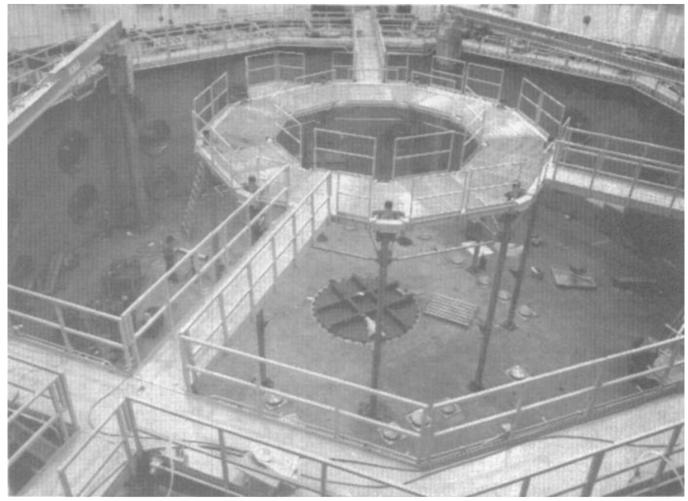

Figure 3. Accelerator tank with center-section work platform.

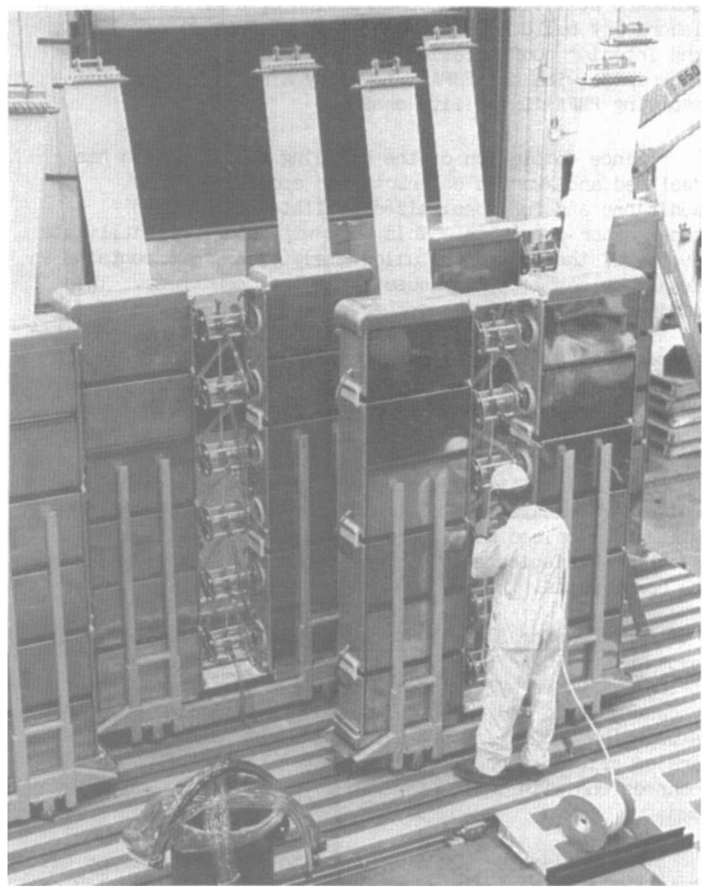

Figure 4. Marx generator during assembly.

Other components of the energy storage system--including charge busses, trigger lines, filters, grounding relays, a dump resistor, trigger generators, and trigger and main transfer switches--were installed throughout the second half of 1984 and into early 1985, mostly ahead of schedule. Low-voltage subsystem tests, starting with the trigger system and switching elements, began in April 1985. Full low-voltage and high-voltage system testing is scheduled to begin in July 1985.

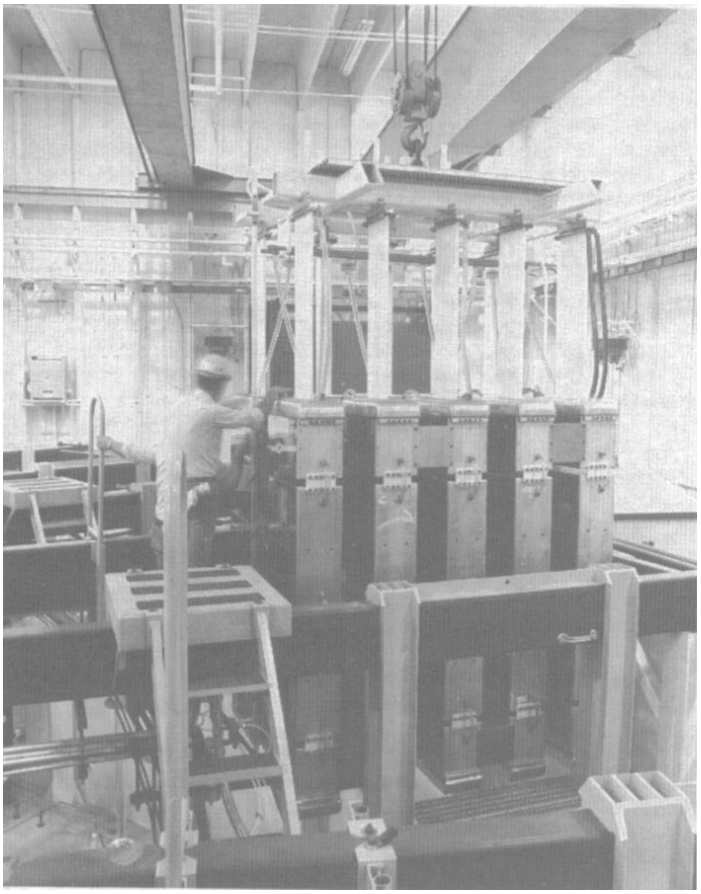

Figure 5. Marx generator being installed in accelerator tank.

Pulse Forming System: Assembly of some pulse forming components is well under way, while others are in the fabrication stage. The water-insulated, water-dielectric pulse forming section of PBFA II contains 36 coaxial modules, each fed by a Marx generator. Each module consists of an intermediate storage capacitor, a laser-triggered gas switch, three increasingly-short pulse forming lines (each with an array of self-breaking pin switches), a coaxial-to-flat-plate transition with polarity inverter, and a transmission line to the vacuum interface. Figure 6 shows a prototype of a pulse-forming module undergoing test in the demonstration accelerator. Associated with the pulse forming system, but not located with the other components, is the laser trigger system. More detail on this system is available elsewhere [1].

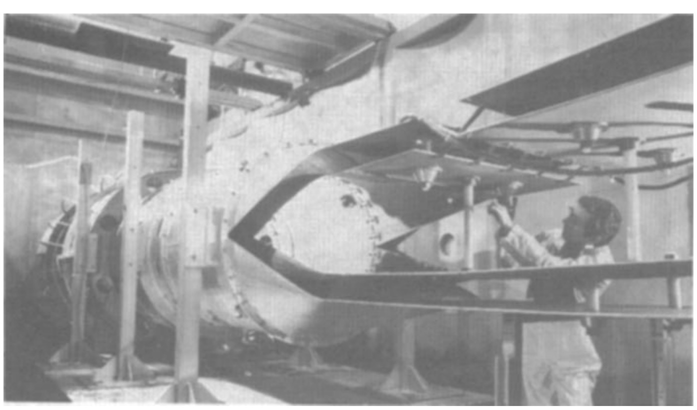

Figure 6. Prototype of pulse forming module.

All intermediate storage capacitors have been received and installed. Figure 7 shows these capacitors in place on the inside of the oil-water wall. Most of the parts for the high-voltage laser-triggered gas switches are on hand and the switches are being assembled. For the pulse forming lines, the original plan was to receive each set of 36 lines sequentially, installing first all 36 of line 1, then all 36 of lines 2 and 3. Fabrication problems, created by difficulty in achieving the necessary tolerances, have caused all three sets of lines to be a few weeks to a month or two late, a situation that has led to a change in the assembly procedure. All three pulse forming lines and the transition section will be installed in each module before the assembly crew moves to the next module. This procedure, now scheduled to go on through July and August 1985, will allow more efficient assembly than the original plan, but it will delay tests of the gas switches until November 1985. The rest of the pulse forming components are being fabricated and are well enough on schedule not to affect accelerator assembly and testing.

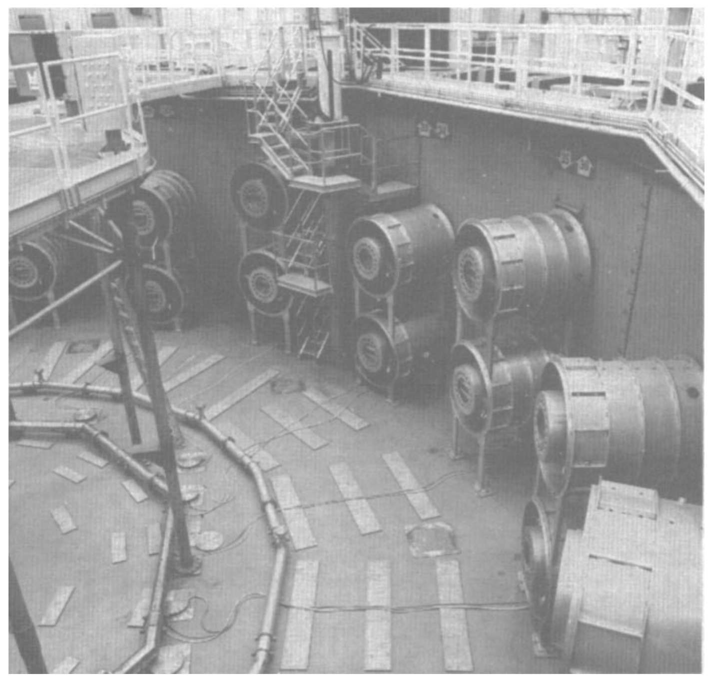

Figure 7. Intermediate storage capacitors installed in accelerator tank.

To trigger the gas switches located between the intermediate storage capacitors and the pulse forming lines, a laser under the PBFA-II tank will produce a beam that will be split into nine beams. Each of the nine beams will be split into four beamlets which will travel up a vertical column into the water section of the accelerator to trigger four gas switches. The baseline for this system is a 4-joule Helionetics KrF laser, which is now undergoing tests. The backup, which will be used if the primary laser cannot be delivered on time, is a Lambda Physik commercial model that will supply just enough energy to trigger the switches. Except for the lasers, all major hardware has been received. Assembly of the laser table, the main distribution table, and the nine vertical optical tables has been proceeding well since the beginning of 1985.

Front End: The front end of PBFA II consists of the components that carry the power pulse from the pulse forming section to the target: the vacuum insulator stack, the vacuum convolutes (or magnetically insulated transmission lines), the plasma opening switch, and the diode. The vacuum insulator stack is a cylindrical assembly of alternating acrylic and aluminum rings, approximately 12 ft in diameter and 18 ft high. This stack separates the water section from the vacuum section and passes the power pulse from the pulse forming hardware to the vacuum convolutes. The metal parts are being fabricated by a single contractor. Manufacture of the acrylic parts is more complicated. Since production of large acrylic castings of the necessary quality proved difficult, Sandia has developed sources for the castings, which are being machined by another contractor and annealed at Sandia. The vacuum insulator stack has been a problem area, but fabrication is now proceeding satisfactorily and installation should begin in September 1985.

The vacuum convolutes, which carry power from the insulator stack to the load, consist of large metal cones and toroids that are now being fabricated for delivery in September 1985. Mounted in the vacuum convolute area near the diode, the plasma opening switch (POS) shortens the final pulse, increasing voltage and power. This switch requires a large-area source (20x86 cm) driven by a small pulser ($<0.1 m^3$). Experiments and analysis at Sandia and the Naval Research Laboratory have led to a design which is now being finalized for the POS. Procurement of the many components that make up the POS system is in progress.

The remaining part of the front end is the applied-B lithium ion diode. Choice of this diode as the best candidate for igniting a pellet placed stringent requirements on several other parts of PBFA II, both to supply the necessary high voltage and to diagnose performance. All parts of the diode are now being fabricated except the cones that form the upper and lower cathodes. Assembly is scheduled for November 1985. The front end components also require many handling fixtures, because large, heavy parts must be installed with precise alignment in an area sharply limited in space. Design of the fixtures is underway.

PBFA-II and Support System Characterization

Phase II of the PBFA-II program, Characterization/ Optimization, will intervene between the first shot in January 1986 and full operation of the accelerator. During this transition, expected to last one year, both PBFA II and its specialized support systems will be characterized and integrated. At the time of the first shot, the accelerator will be fully assembled but not optimized. Support systems will be complete and operational but may lack some desirable features. In short, the facility will include all design features required for initial operation, but it will not be ready for regular experimental use. The characterization phase is therefore needed to

- make design modifications that tests show to be required
- characterize PBFA II and optimize its performance
- integrate and optimize support systems
- perform initial tests of ion diodes
- establish stable operating modes for the accelerator
- improve turnaround time between experiments
- improve the learning rate from experiments.

Preparations for the characterization period began long before the first shot. Planning began in September 1983. In January 1985, some characterization work began, overlapping the last year of construction. Certain deliverables of this phase--particularly those that increase operating efficiency--will be in place before the construction phase ends. This overlap allows progress from construction to full operation to begin immediately after the first shot.

The strategy of characterization and optimization includes two stages. During the first, a debugging stage, several 36-module accelerator shots will exercise the entire machine from the energy storage section to the diode. These shots will also test the support systems. Even though accelerator performance and data acquisition will not be optimized at this time, these tests will reveal problem areas that may require modification or re-engineering. After debugging, a second characterization stage will begin. Accelerator subsystems and support systems that do not require changes will be methodically characterized to precisely determine their operating parameters and to make any desirable minor modifications. During this stage, capability of the data acquisition system, control/monitor system, and perhaps other support systems will be increased to the level required to support the experimental program. Thus characterization will move from coarse to fine evaluation and adjustment. The product of the characterization period will be a research facility capable of being used for a program of experiments.

Source Development

Phase III of the PBFA-II program is Source Development. This phase, expected to span the period from July 1986 through September 1987, has two objectives: (1) characterization and optimization of the ion diode, and (2) optimization of the energy and power available to the target. Attributes of the ion diode and ion beam that must be mastered during this phase include prompt and uniform initiation of the ion source, purity of the ion source, control of the diode impedance, and neutralized transport of the ion beam. An array of high-quality beam and target diagnostics will be required both to make rapid progress in these areas and to measure the properties of the ion beam before target experiments can begin. Success in this phase will be demonstrated by having a high beam focal intensity and an adequate dwell time on target. Demonstration of a good correlation between experimental measurements and comprehensive simulations of beam transport and focusing will also be important.

Target Campaign

Phase IV of the PBFA-II program is the Target Campaign. It is during this phase that the program might reach its goal of igniting thermonuclear fuel in the laboratory. Objectives during this portion of the PbFA-II program include

(1) performance of ion beam coupling experiments
(2) development of target diagnostics for determination of beam focal parameters at a "real" (i.e., not a diagnostic) target
(3) characterization of an ion-driven hohlraum
(4) optimization of the hohlraum for implosion experiments
(5) ignition of a fuel-filled target
(6) performance of various weapon-physics experiments.

Success in this portion of the program will be marked by demonstration of target ignition and by initial exploration of the physics of high-gain targets.

Acknowledgments

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